ANALYSIS OF A FEASIBLE PULSED-POWER SUPPLY SYSTEM FOR AN UNMANNED AERIAL VEHICLE

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Abstract

More Electric Aircraft technology enables the power supply of electric energy weapons such as high-power microwave and laser weapons. Aspects of electric power generation, energy storage, distribution and pulse-conditioning systems for the power supply of directed energy weapons in Unmanned Aerial Vehicle are addressed in this paper.

A trend in aircraft design is to electrify more parts of the aircraft via the concept of More Electric Aircraft (MEA) and its technology which allows for increased electric power consumption. Thus, MEA technology enables the power supply of weapons and protection systems that are using electric energy. Among these devices directed energy weapons such as high-power microwave (HPM) and laser weapons are feasible. Such systems require high power pulsed electric energy with, thus imposing new requirements of on-board power supplies.

In the demonstrated concept it is important to analyze power losses and efficiency as well as weight and volume in order to evaluate the possibility to adapt the system in an UAV.

1 Introduction

In the process of designing an electric power supply system for an aircraft, parameters like low weight and low losses are important [1]. An autonomous Unmanned Aerial Vehicle (UAV) is an interesting platform for Electric HPM or laser weapons [2]. In operation of an UAV, an installed HPM weapon is an interesting alternative to conventional weapons since the UAV can fly to the target area and deliver the HPM radiation close to the target.

A feasible system requirement for the peak electric power in the HPM-systems is 6 GW. The needed electric field strength to cause the effect of damage or disturbance in electronic equipment as radiated from the HPM system is not treated in this paper. The advantage with the analyzed technology is that other damages to people or property is not caused.

It is assumed that the proposed 6 GW HPM weapon studied in this report can be used up to a distance of approximately 500 m, see figure 1.

The question to be answered in this paper is if it is possible to equip UAV:s with such HPM systems.

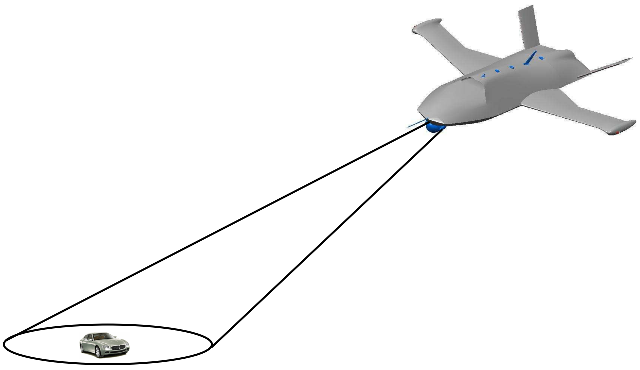

Fig.1. UAV with HPM Weapon

System aspects of electric power generation and energy storage as well as distribution of the required electric power for a directed energy weapon integrated into an Unmanned Aerial Vehicle (UAV) are dealt with in this paper. A draft specification is given in table 1.

A conceptual electric power supply system is sketched and analyzed together with the required components. The problems of system control and installation issues are also addressed. An essential function in HPM-system is the energy storage. Energy can be stored in flywheels, inductances or capacitors.

Table. 1.

HPM Draft Specification	
Electric Power	6 GW
Voltage to Microwave Generator	600 kV
Supply voltage	30 kV
Pulse length	200 ns
Pulse frequency	20 Hz
Number of pulses	continuous
Electric supply power	28 kW
Weight (max)	150 kg
Length	1200 mm
Diameter	300 mm

2 Design

Components in the electric power supply system include electric power generators, a high voltage generator, and intermediate storage of electric energy and pulse-conditioning systems in form of a Marx-generator. In addition a microwave radiation source, comprising a virtual cathode oscillator and antenna is required.

A block diagram for the HPM-system system can be seen in figure 2.

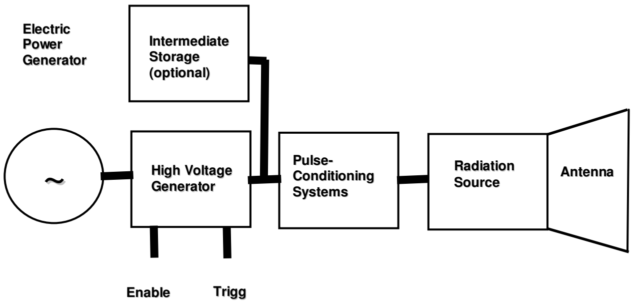

Fig. 2. The HPM System block diagram

The advantage of the proposed design is its simplicity and the fast response.

With a concept where the pulse frequency is chosen such that the required average power complies with the available power, no intermediate storage is needed.

To trigger the weapon normally an enable switch shall be closed and then, to fire the weapon a trigger signal is activated. The enable command signal is activating the system.

To trigger the system one of the gaps in the Marx-generator could be triggered. An alternative method could be to use self-triggered gaps using a ramp voltage controlled by the high voltage generator. The high voltage ramp to charge the Marx-generator must be very fast if used for trigging. The enabled system will be charged to a safe level, which will ensure that the weapon is not triggered. This will represent a standby mode.

The time for ramping up the high voltage generator and charging of the Marx-generator can be approximately 7 ms. During this period of time an UAV equipped with a HPM-system can move approximately a distance of less than 3 m. During a mission this delay can be compensated for.

2.1 Power Generator

The primary energy source is a generator with conversion from mechanical to electrical energy. In an UAV system, one or two generators supply the UAV-systems. An output of approximately 20-30 kW in a medium size UAV can by available for electric weapons. The generator output shall be transformed to a high voltage input for the HPM system.

The generator studied here is a novel 3-phase axial flux machine [10]. The continuous output power is 40 kW with peaks up to 60 kW. In figure 3 an example of such machine concept is shown.

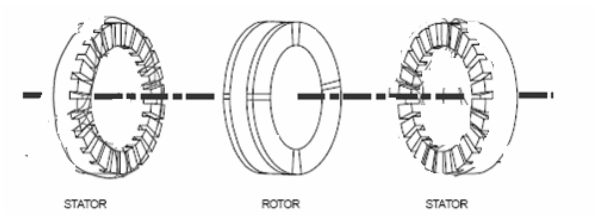

Fig. 3. An example of an axial flux machine with a single rotor-double stator assembly, see [11]

The outer radius of the studied machine is 105 mm, the inner radius 82 mm, and the length of the machine 47 mm. The mechanical speed is 20 000 rpm, which with 32-poles gives an electrical frequency of 5330 Hz. The weight of the generator is estimated to 10 kg.

2.2 High Voltage Generator

The high voltage generator is supplied with electric power from the permanent magnet generator (PMG) with variable frequency and voltage. The conceptual high voltage generator is based on a Transformer Rectifier Unit (TRU). The TRU constitutes a multi-pulse design in order to reduce the distortion of the aircraft generator output voltage. By using a 12-pulse rectifier design the output voltage can by built by adding the contribution from two six-pulse bridges, resulting in 30 kV output with 15 kV per bridge, see figure 4.

The transformers can use toriods based on amorphous alloys offering the possibility to work with higher frequency and low losses. The voltage from the TRU needs to be controlled, due to the non controlled output voltage from the generator. Furthermore a power switch contactor must be included in the high power generator. The power switch contactor will activate the standby mode when enabling the system.

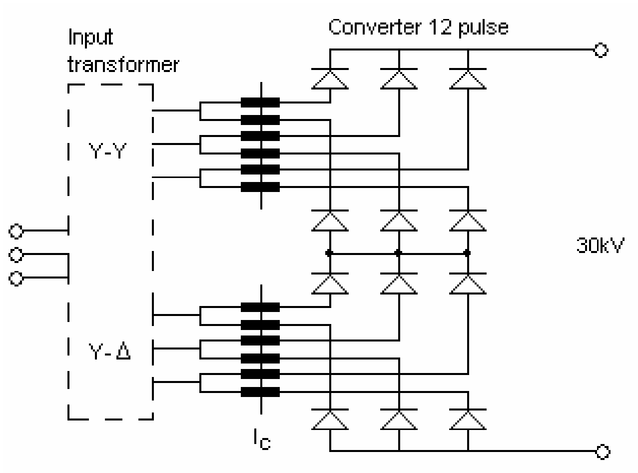

Fig. 4 The high voltage generator

30kV requires an insulation of minimum 1 mm with a high performance insulation material and even more important a proper geometric design. Air cooling might be sufficient in this application. Oil cooling could be an alternative which would improve insulation. To overcome disadvantages such as high humidity and low air pressure it is proposed that the volume shall be filled with an inert gas. An initial design approach indicates a possible weight of approximately 15 kg for the high voltage generator with an output voltage of 30 kV.
The conclusion is that a core made of an alloy in the Metglas 2605-family [12] is preferable, due to low losses and high magnetic flux density

yielding low weight. The high reliability and robustness also represents a significant value adding to the attraction of magnetic amplifiers in aircraft applications.

The sizes of the cores are based on (1) the required magnetic flux. The induced voltage E, is given by

$$E = 4.44 \cdot \hat{B} \cdot A \cdot N \cdot f \qquad \text{[V]} \qquad (1)$$

where B is the flux density, A the core area, N the number of turns, and f the frequency. Iron area, number of turns and frequency and consequently gives the core weight. The amorphous alloys 2605TCA data is extracted [13] to give the equation (2) expressing the core losses as a function of frequency and magnetic flux.

$$P = 88 \cdot 10^{-6} \cdot f^{1.57} \cdot B^{1.7} \qquad \text{[W/kg]} \qquad (2)$$

Efforts were put on analyzing the magnetic circuits in the high voltage generator.
The analyses of the transformers yielded a weight of 2.5 kg and losses of 260 W. A corresponding analyses of the magnetic amplifier yielded a weight of 3.2 kg and losses of 340 W.

The total estimated weight of the high voltage generator including transformers, magnetic amplifiers, wiring, insulation, rectifier diodes, power regulation, internal power supply, housing, filters, protective circuits and connectors is 15.0 kg. This weight is very conservative depending on precautions regarding the 30 kV insulation.

The evaluated losses includes the losses from the transformers, magnetic amplifiers, regulation circuits, internal power supply, rectifier diodes and filtering is estimated to be 1400 W. Estimated total losses enable an efficiency of the high voltage generator to be 93%.

2.3 Energy Storage

With optional energy storage, energy can be supplied to the pulse-conditioning system. Examples of devices for intermediate storage of electric energy are batteries, flywheels and capacitors. The purpose with e.g. a capacitor bank is to buffer the input power to the pulse-conditioning system. The advantage is that the voltage from the high voltage generator can be stabilized, resulting in a more stable 30 kV DC-level, as well as the possibility of reduced power rating for the generator and the high voltage generator.

The proposed conceptual HPM Weapon system described in this paper is designed without intermediate storage. Thus the power supply system is designed for "continuous power supply".

2.4 Pulse-Conditioning System

Examples of components in pulse-conditioning systems are inductors, capacitors, switches and magnetic compressors. Pulse shaping, with e.g. high voltage generation and power conditioning can be performed with a Marx generator.

2.4.1 Marx Generator

An energy storage bank (capacitor or line) is generally used when a high impulse voltage or current is needed. A Marx generator comprises a series-parallel connected capacitor-resistor bank. The capacitors are charged in parallel and discharged in series through spark gaps. The behavior of the spark gap is the most important issue regarding the amplitude of the impulse and the reproducibility, see [1]. A 20 stage Marx generator is studied here, shown in figure 5.

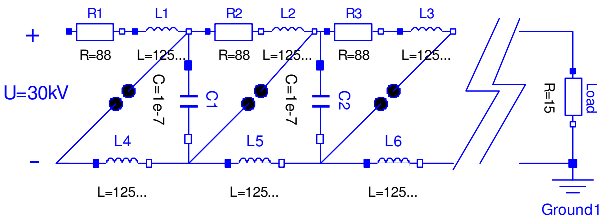

Fig. 5. The studied Marx generator

The output power is 6 GW and the pulse length 200 ns which correspond to a pulse energy of 1200 J. The energy *W* stored in a capacitor (3) is given by

$$W = \frac{1}{2}CV^2 \qquad [J] \qquad (3)$$

where *C* is the capacitance and *V* is the voltage. A 20 stage Marx generator with 30 kV per stage gives a terminal voltage of 600 kV, and thus 300 kV across a matched load. The minimum value of the capacitors can be calculated according to equation (3) and (4),

$$C = \frac{1200 \times 2}{\left(20 \times 30 \cdot 10^3\right)^2} \times 20 = 1.3 \cdot 10^{-7} \ [F] \qquad (4)$$

The capacitances are discharged in series and thereby the factor 20. The repetition frequency of the whole process, i.e. charging and discharging of the capacitor bank, is chosen to 20 Hz. Due to the high frequency, inductive elements for charging the capacitors are used. The impedance of the inductors during the discharging should be higher than the load impedance and in the same time during the charging process less than the capacitive impedances.

$$\omega L = \frac{2 \cdot \pi}{200 \cdot 10^{-9}} L >> 15 \qquad [\Omega] \qquad (5)$$

$$7800 >> 15 \qquad [\Omega]$$

$$\omega L = \frac{2 \cdot \pi}{50 \cdot 10^{-3}} L << \frac{1}{\omega C} = \frac{50 \cdot 10^{-3}}{2 \cdot \pi \cdot 1.3 \cdot 10^{-7}} \quad [\Omega] \ (6)$$

$$0.0314 << 61000 \qquad [\Omega]$$

From equations (5) and (6) the value of the inductances in fig. 5. can be set to 125 µH. Since the inductive and capacitive components have oscillating effect on the circuit then resistors are used for damping the oscillation amplitudes.

A minimum value of the damping resistance can be estimated according to

$$R = 2\sqrt{\frac{L}{C}} = 2\sqrt{\frac{2 \cdot 125 \cdot 10^{-6}}{1.3 \cdot 10^{-7}}} = 88 \ [\Omega] \qquad (7)$$

The weight of the device is estimated to 20 x 1.6 = 32 kg where the dominant part is the capacitance [8], for 0.13 µF, 30 kV PMR capacitors. Assuming an efficiency of the Marx generator of 0.9, [17] the estimated losses in the Marx generator is approximately 2.5 kW.

2.4.2 Spark Gaps

In high voltage applications, ordinary semi conductor switches are not yet suitable, even if the development is rapid. In these applications "voltage-dependent" or "time/space-dependent" spark gap mechanisms are used. The repetition frequency is ensured usually by using gaseous medium, as a separator of the electrodes. In order to reduce the electrode surface damage of the arc, tungsten can be used, see figure 6.

By using the standard formulas for a cylinder capacitor and a coaxial cable the stray capacitance and inductance of the spark gap can be estimated.

Fig. 6. UV-triggered spark gap [9], 10-50 kV, up to 50 kA

$$C = \varepsilon_r \varepsilon_0 \frac{2\pi l}{\ln\left(\frac{r_2}{r_1}\right)} \qquad [F] \qquad (8)$$

$$L = \mu_{r,2}\mu_0 \frac{l}{2\pi}\ln\left(\frac{r_2}{r_1}\right) + \mu_{r,1}\mu_0 \frac{l}{8\pi} \quad \text{[H]} \qquad (9)$$

With the values l = 217 mm, r_2 = 76 mm, $\frac{r_2}{r_1} = 5$, $\mu_{r,2}$ = $\mu_{r,1}$ = 1, and ε_r = 2.2 inserted in equations (8) and (9), L is 80 nH and C is 7.5 pF. The weight of the device is estimated to 20 × 0.4 = 8 kg, see [8].

2.5 Microwave Radiation System

The microwave radiation system comprises a radiation source, a waveguide and an antenna. To minimize weight and volume, the parts of the system must be well integrated. A gross estimate of the weight of a system as discussed below is 25 kg, and the estimated radiated electric field strength at the target is 3.4 kV/m.

2.5.1 Radiation Source

One categorisation of radiation sources is based upon their frequency content [16], and one possible division into different categories is:

- Narrow-band devices
- Moderate bandwidth devices
- Ultra-wide band devices

The specified value of the pulse length and the requirement of a strong centre frequency limit the choice of radiation source to be a narrow-band vacuum-pumped radiation source. There exist several types of such devices, including magnetrons, klystrons, travelling wave tubes, magnetically insulated line oscillators (MILO) and virtual cathode oscillators (vircator). [14,15]. Magnetrons, klystrons and travelling wave tubes require an external magnetic field to operate that makes them heavy and bulky. The MILO and the vircator do not require any external magnetic field. Among these two, the current research is concentrated upon the vircator and thus the vircator is chosen for the analysis here. The centre frequency of the generated microwave radiation in a vircator is governed by the applied voltage, the distance between anode and cathode, and the shape of the resonance cavity. A larger anode-cathode distance gives a longer distance for the electrons to travel between the real and virtual cathodes which results in a lower emitted microwave frequency. There exist several versions of the vircator where the reflex triode as illustrated in figure 7 is one. The output frequency (10) of the microwave radiation from a planar vircator can be estimated by the following expression, which is derived from a straight-forward 1D-model [5],

$$f = \frac{5}{4\pi}\sqrt{\frac{je}{\varepsilon_0 \gamma m \beta c}} \quad \text{[Hz]} \qquad (10)$$

where

$$j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{U^{3/2}}{d^2} \qquad (11)$$

and e is the electronic charge, m is the electronic mass, ε_0 is the permittivity of free space, c is the speed of light, U is the applied voltage and d is the anode-cathode gap distance. γ is the relativistic factor $(1-\beta^2)^{-1/2}$ with

$$\beta = \sqrt{1 - \frac{mc^2}{eU - mc^2}} \, . \qquad (12)$$

For example, to radiate in the upper C-band, that is, around 8 GHz, using a power supply that gives 300 kV across the load, the required anode-cathode gap distance is about 9 mm. The size of the cavity must be at least one wavelength, which is about 0.04 m, resulting in a volume less than 10^{-4} m^3. However, to work properly, a Bragg reflector must be present at the feed of electric power to avoid that the microwave radiation escapes in an unwanted direction.

To have an optimal power transfer, the impedance of the vircator (13) must be matched to the one of the Marx generator. An estimate of the vircator impedance is given by

$$Z = \frac{U}{jS} \qquad [\Omega] \qquad (13)$$

where S is the cross-sectional area of the electron-emitting part of the cathode. A voltage of 300 kV across the vircator and a cathode with a radius of 37 mm gives an impedance of the vircator of 15 Ω.

A typical efficiency of a vircator is about 5 %, that is, if the electric power is 6 GW, then the microwave power is 300 MW. The mean power consumption of the vircator is the power times the duration of each pulse times the pulse frequency, thus

$$6\ \text{GW} \times 200\ \text{ns} \times 20\ \text{Hz} = 24\ \text{kW}.$$

Using the assumed efficiency of 5 %, 95 % will be heat losses, thus around 23 kW must be cooled off.

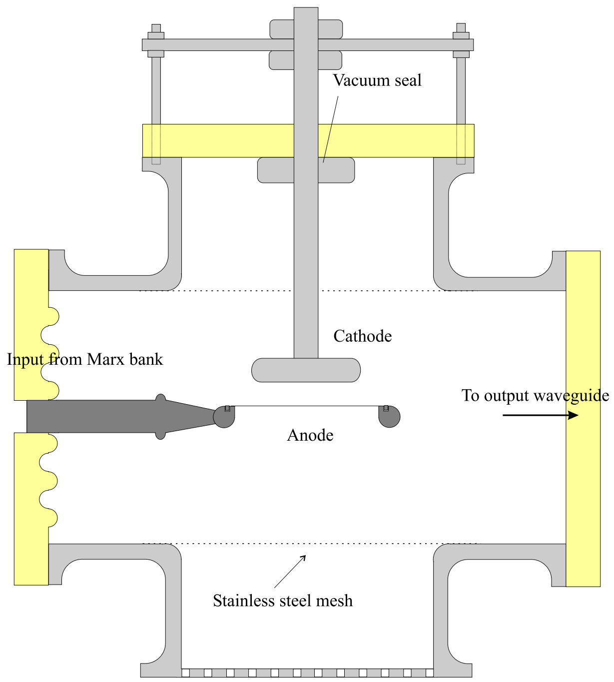

Fig. 7. The reflex triode type of the vircator family [3,4]

2.5.2 *Waveguide*

A waveguide is used to connect the radiation source with the antenna. A circular waveguide for the upper C-band has a radius of about 0.03 m. To be called a waveguide, it must be at least a few wavelengths long, in our case at least 0.1 m.

If the waveguide is not evacuated, the maximum power through it is given by equation (14) (rectangular waveguide) [7]

$$P_{\max} = 2.6 \cdot 10^{13} \left(\frac{E_{\text{bd}}}{f_{\max}} \right)^2 \qquad [\text{W}] \qquad (14)$$

where E_{bd} is the breakdown electric field strength of the medium and f_{max} is the highest frequency of the fundamental mode. To transmit 300 MW at 8 GHz requires a medium with field strength of 27 MV/m. Air at sea-level pressure and room temperature has field strength of 3 MV/m. Since the breakdown field strength scales linearly with pressure, an overpressure of more than nine would achieve sufficient breakdown field strength. Other solutions include replacing air with a gas with a higher dielectric strength, for instance sulphur hexafluoride, or evacuating the waveguide.

2.5.3 *Antenna*

The microwave radiation must leave the source and waveguide, and start to propagate in open space towards the target. The antenna does the job of directing the radiation towards the target. With a bigger antenna, the better the radiation is directed. Using a horn antenna with an opening of 0.3 m, the optimum length of the antenna is about 0.8 m and with that length, the directivity is 25 dB [6].

3 Conclusions

An HPM weapon can constitute an important part of an Unmanned Aerial Vehicle (UAV).

A total weight of the system could be:

Generator	10 kg
High voltage generator	15 kg
Marxgenerator	40 kg
Vircator and waveguide	15 kg.
Antenna	10 kg
Installation /wiring	20 kg
Total system weight	110 kg

The weight requirement is thus feasible to reach. Critical issues are to achieve a high power density system with low power losses and an adequate cooling.

4 Acknowledgments

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